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(54) **Post transmission dispersion compensation of amplifier induced frequency jitter**

(57) An optical communications system has a transmission path including an optical communications fibre 2 having an input port 3 and an output port 4. A compensating element 5 to compensate for a perturbation such as soliton jitter noise in an optical signal transmitted along said transmission path is coupled to the output port, which introduces dispersion of equal magnitude but opposite sign to that of the signal which has passed through system 1. Alternatively, (see fig. 5), a four wave mixer is corrected between identical compounds 1, 2, 7, 8 for spectrally inverting (by phase conjugation) the signal prior to re-transmission along a compensating fibre loop 8.

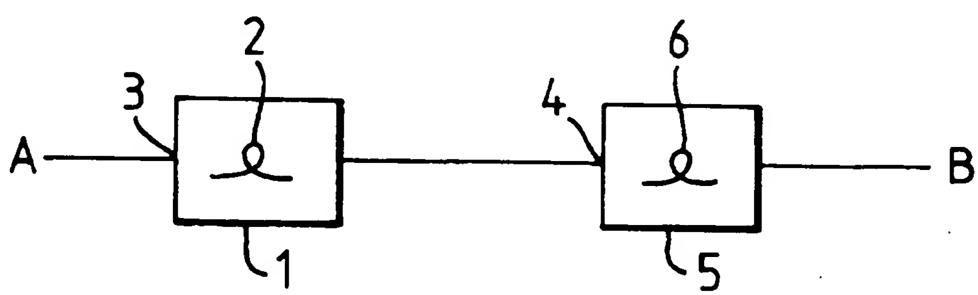

Fig. 4

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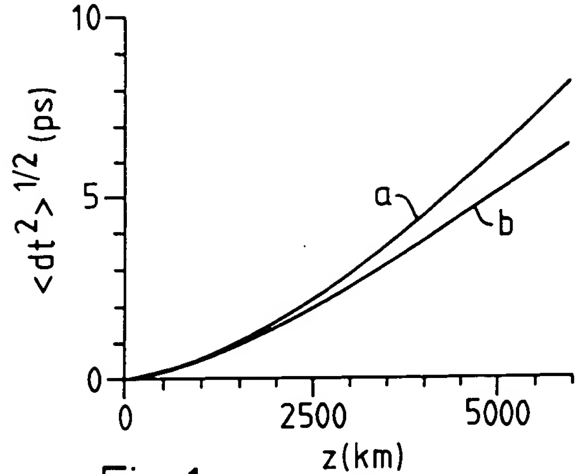

Fig. 1

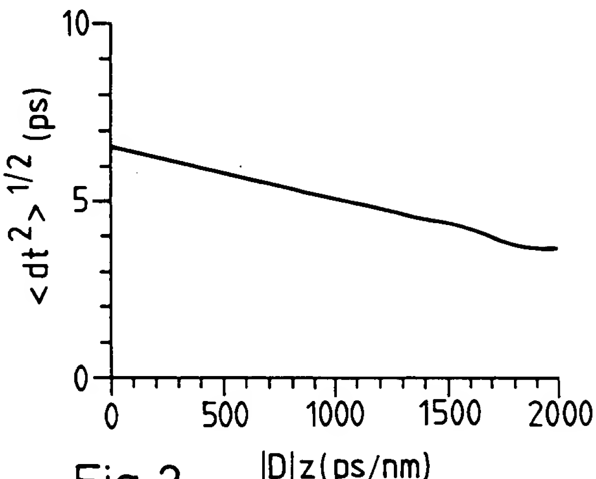

Fig. 2

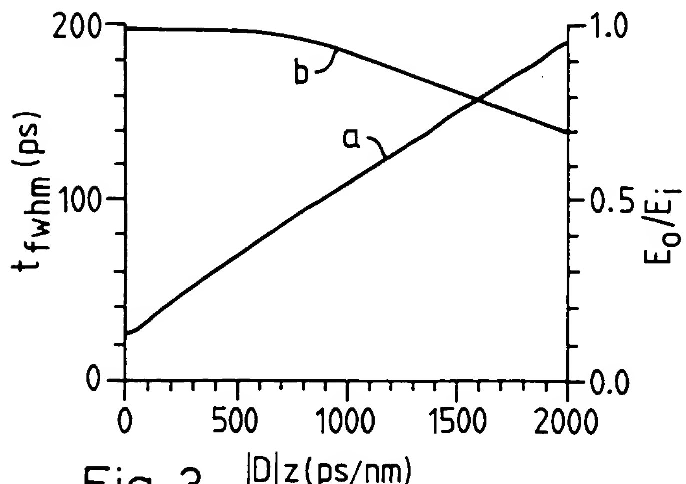

Fig. 3

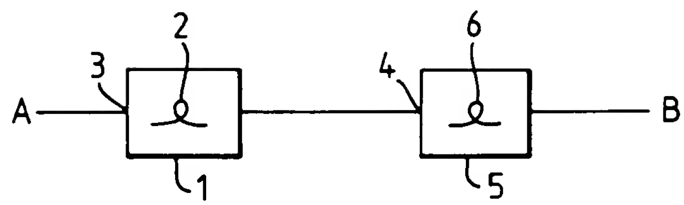

Fig. 4

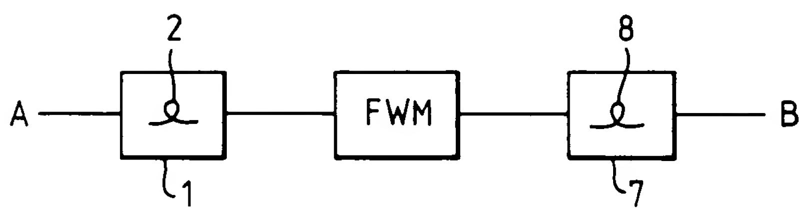

Fig. 5

Optical Communications

This invention relates to optical communications and, in particular, to methods of enhancing the performance of optical communications systems.

In long-distance, periodically amplified soliton communication systems, the principal limit to transmission line capacity arises from spontaneous emission noise introduced at each optical amplifier. The resulting effect, first analysed by Gordon and Haus (JP Gordon and HA Haus, Opt. Lett. 11 665 (1986)) is a timing jitter in the soliton arrival time at the receiver, whose magnitude limits the bit interval and therefore the data rate. Recently it has been shown that soliton timing jitter can be reduced by inline optical filters. (A. Mecozzi, J.D. Moores and Y. Lai Opt. Lett. 16 1841 (1991), Y. Kodoma and A. Hasegawa Opt. Lett. 17 31 (1992)) We have found that the jitter can also be substantially reduced by post transmission dispersion compensation.

According to the present invention there is provided an optical communications system having a transmission path including an optical communications fibre having an input port and an output port wherein a compensating element to compensate for a perturbation in an optical signal transmitted along said transmission path is coupled to the output port.

According to a particular aspect of the present invention there is provided a soliton communication system in which soliton timing jitter is at least partially compensated by the introduction of post transmission dispersion compensation.

The invention will be described, by way of example with reference to the accompanying drawings, in which:-

Figures 1 to 3	are graphical representations of experimental results, and
Figures 4 and 5	are schematic drawings of communications systems in accordance with specific embodiments of the invention.

Analysis shows that the deviation in a soliton's mean position $\langle\Delta t^2\rangle^{1/2}$, is proportional to the magnitude of the of the fibre dispersion $|D|$. The principle underlying this dependence is that the amplifier-induced frequency jitter is translated from frequency to time, during propagation between amplifiers, via dispersion. For any individual period complete compensation may be achieved by the addition of linear dispersion of equal magnitude and opposite sign. Analysis indicates that in a concatinated chain of amplified sections $\langle\Delta t^2\rangle^{1/2}$ can be reduced by one half if post transmission dispersion compensation of half the previous total dispersion is introduced. However, since dispersion leads to temporal broadening, the maximum permissible dispersion compensation may be limited by the soliton bit interval.

To estimate the limit to dispersion compensation, we may consider the effect of a purely dispersive element on a Gaussian pulse, $E = E_0\exp\{-t^2/2t_o^2\}$. At $\lambda = 1.55\mu m$, the maximum total dispersion is given by

$$(z.|D|)_{max} = \frac{t_o}{1.275}\left[\left(\frac{p}{f}\right)^2 - t_o^2\right]^{1/2} \qquad \text{(ps/nm)}$$

where p, the bit interval half-width, and t_o are in ps and f is a factor determined by the final fractional energy required within the bit interval. For example, final fractional energy requirements, E_o/E_i, of 0.7 and 0.9 correspond to f=1 and f=1.6, respectively. Thus for a 5GBit/s system operating with 20ps (fwhm) pulses and f = 1.6, this simple formula predicts a maximum dispersion compensation of 580ps/nm, or approximately 1/5th of the optimum for a transmission line of total dispersion 6000ps/nm.

To demonstrate the effectiveness of dispersion compensation we show Figures 1-3, summarising data for a set of 200 realisations of a 5GBit/s, 6000km long transmission line with 20ps solitons and D = 1ps/nm. For partial reduction of

Gordon-Haus jitter, our calculation has included inline Lorentzian filters of 30x the soliton bandwidth. Their effect is to reduce $\langle\Delta t^2\rangle^{1/2}$ from 8.2ps to 6.6ps after the 6000km propagation, as shown in Figure 1. Figures 2 and 3 show the additional reduction obtainable with increasing dispersion compensation and the corresponding monitors of pulse width and bit interval energy. It can be seen that significant reductions in $\langle\Delta t^2\rangle^{1/2}$ can be achieved, with negligible bit energy leakage for total dispersion compensations of up to 1000ps/nm. Therefore this straightforward and "cheap" post propagation technique may be used to enable soliton operation of already installed and unfiltered communication systems. Moreover, it offers additional returns for weakly filtered soliton systems and possible application to frequency multiplexed systems. The principle is to use phase conjugation for compensation of dispersion, non-linearity and amplifier noise induced jitter.

In the systems outlined above, we use a dispersive compensating element of opposite sign at the end of a soliton communication system to reduce temporal pulse jitter. If total dispersion of half the system can be used, the RMS jitter is halved. Linear dispersion in the compensating element, however, leads to temporal broadening thus reducing the compensation which can be achieved.

In an alternative embodiment of the invention, we spectrally invert the signal (preferably by phase conjugation) and then re-transmit it in a fibre. The fibre into which the signal is subsequently launched may simply be a compensating loop of appropriate length or it may be a further transmission stage of the communications path. This scheme will perform dispersion compensation but has the advantage of allowing soliton propagation in the compensating part and thus eliminates pulse broadening, permitting a full factor of half post transmission compensation. Additionally, the use of this technique also compensates for linear dispersive broadening (not present in

soliton systems) and nonlinear interactions, which latter are very important in both NRZ <u>and</u> soliton systems.

Our method of compensation uses four-wave mixing (4WM) in a fibre to perform the phase conjugation. In the following description, the term four-wave mixing also includes any other phase conjugation scheme.

Compensation using four-wave mixing can be applied to soliton and NRZ systems but may take slightly different forms in each case.

For soliton systems, at the end of the system, the jitter variance is

$$\langle \delta t^2 \rangle = \sum_{j-1}^{N} (D_1 Z_a j)^2 \langle \delta\omega^2 \rangle$$

where D_1 is fibre dispersion (ps/nm/Km), Z_a is amplifier spacing (Km) and N is the number of amplifiers. Spectral inversion leads to $\delta\omega \rightarrow -\delta\omega$. If fibre of dispersion $+D_2$ and length L_2 is added the jitter is then

$$\langle \delta t^2 \rangle = \sum_{j-1}^{N} (D_1 Z_a j - D_2 L_2)^2 \langle \delta\omega^2 \rangle$$

which is minimised for $D_2 L_2 = D_1 Z_a N/2$. Thus if total dispersion of the same sign but half the original system dispersion is added, the RMS jitter is reduced to half its previous value.

For soliton system, other undesirable effects will also be compensated by this approach and in particular soliton-soliton interactions. Solitons attract and collapse if they are too close or propagated too far. This attraction is reversed in the compensating link - but since it is half the effective length only 50% reversal is achieved, i.e. back to half way down the original system.

The principle is that the evolution involves dispersion and nonlinearity and is described by the nonlinear Schroedinger equation

$$i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u = 0$$

The transformation $u \rightarrow u^*$ (phase conjugation) is equivalent to propagation reversal, i.e. running the equation backwards in direction and time. Thus, in principle, exact compensation is possible for pure NLS effects if the compensating element is equal in length to the transmission line. However, only half the length is desirable for the compensation of noise induced jitter (not in the NLS).)

In soliton systems jitter and SPM compensation can be achieved if the phase conjugation is performed at the midpoint of the system. The jitter reduction is exactly as above, i.e reduction to half its otherwise RMS value, but the soliton-soliton interaction and any other NLS effects are exactly balanced at the end of the system. In fact, if the phase conjugation is performed two-thirds of the way down the system, the RMS jitter is reduced by a factor of 3 but the NLS undoing is only 50%, as explained above. The absolute optimum is to perform phase conjugation at every amplifier - this eliminates all jitter and finds practical application in shorter distance systems and NRZ systems where it permits larger amplifier spacing.

NRZ systems are not limited by noise induced jitter, but may be limited by nonlinear effects and in particular by spectral broadening.

In these systems phase conjugation can give compensation for nonlinear and dispersive effects either by post transmission processing or by intermediate operation. In the post transmission processing case it is desirable to have a dispersive and a nonlinear length equal to the system length. In the proposed system TAT12/13 trans-Atlantic communications cables, the intention is to operate with D=0. Thus the second fibre must also have D=0. However, its length can be reduced by

increasing the power relative to the power in the transmission part. Here again four-wave mixing at the midpoint will give exact compensation provided the effect is due to dispersion and nonlinearity. Any nonlinear or frequency dependent loss will reduce the exact balance.

Referring now to Figure 4, a fibre optic communications system 1 passing signals from A to B includes an optical fibre 2 and has an input port 3 and an output port 4. Coupled to the output port is a compensating element 5 including an optical fibre 6 and adapted to introduce dispersion of equal magnitude but opposite sign to that of the signal which has passed through the system 1. In an alternative embodiment (Figure 5) a four wave mixer FWM is connected between substantially identical components 1,2 7,8 of the communications system.

Claims

1. An optical communications system having a transmission path including an optical communications fibre having an input port and an output port wherein a compensating element to compensate for a perturbation in an optical signal transmitted along said transmission path is coupled to the output port.

2. An optical communications system as claimed in claim 1 wherein said compensation element comprises dispersive means adapted to introduce into the transmission path dispersion of opposite sign to that of dispersion introduced by said optical communications fibre.

3. An optical communications system as claimed in claim 1 wherein said compensation element comprises inversion means spectrally to invert a signal transmitted along said path.

4. An optical communications system as claimed in claim 3 including a further optical fibre.

5. An optical communications system as claimed in claim 4 wherein said further optical fibre is a further stage in the transmission path.

6. An optical communications system as claimed in claim 4 wherein said further optical fibre is a compensating loop.

7. An optical communications system as claimed in claim 3 wherein inversion means comprises four-wave mixing means adapted to perform phase conjugation.

8. An optical communications system as claimed in claim 7 wherein phase conjugation is performed at at least one amplifier in said transmission path.

9. An optical communications system as claimed in claim 4 wherein the combination of power transmitted along siad further optical fibre and the length thereof is selected substantially to compensate for a selected perturbation is said optical signal.

10. An optical communications system as claimed in claim 9 wherein the length of said further optical fibre is substantially equal to the length of said optical communications fibre.

11. An optical communications system as claimed in claim 9 wherein the length of said further optical fibre is substantially equal to one half of the length of said optical communications fibre.

Patents Act 1977
Examiner's report to the Comptroller under Section 17
(The Search report) -9-

Relevant Technical Fields (i) UK Cl (Ed.M) H4B - BK18 (ii) Int Cl (Ed.5) H04B - 10/18 **Databases** (see below) (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii) ONLINE DATABASES: WPI, INSPEC	Application number GB 9407725.2 Search Examiner D H JONES Date of completion of Search 20 JULY 1994 Documents considered relevant following a search in respect of Claims :- 1-11

Categories of documents

X: Document indicating lack of novelty or of inventive step.

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A: Document indicating technological background and/or state of the art.

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&: Member of the same patent family; corresponding document.

Category	Identity of document and relevant passages		Relevant to claim(s)
X	GB 2268018 A	(DENWA) lines 2-12 page 12	1, 2
X	EP 0531210 A1	(ALCATEL) see Figure 1 and Claim 1	1, 2
X	EP 0500357 A2	(NEC) see Figure 1 and lines 2-20 column 6	1-7 at least
X	WO 85/00483 A1	(NIPPON) see English Language abstract	1

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